

## Characterization of the $V_0$ Domain of the Coated Vesicle ( $H^+$ )-ATPase\*

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The coated vesicle ( $H^+$ )-ATPase is composed of two domains, a peripheral  $V_1$  domain containing the 73 (A subunit)-, 58 (B subunit)-, 40-, 34-, and 33-kDa subunits and an integral  $V_0$  domain containing the 100-, 38-, 19-, and 17 (c subunit)-kDa subunits (Adachi, I., Puopolo, K., Marquez-Sterling, N., Aral, H., and Forgacs, M. (1990) *J. Biol. Chem.* 265, 967-973). In the present manuscript we characterize the  $V_0$  domain with respect to its structural and activity properties. Glycerol density gradient separation of solubilized coated vesicle membrane proteins reveals the presence of an excess of  $V_0$  domains which migrate with a molecular weight of 250,000 and contain the  $V_0$  polypeptides in the same stoichiometry as in the intact  $V_1V_0$  complex. Like the c subunit in  $V_1V_0$ , the c subunit of the free  $V_0$  domain is labeled by [ $^{14}C$ ]N,N'-dicyclohexylcarbodiimide (DCCD) and is extracted by chloroform:methanol. In addition, a monoclonal antibody specific for the 100-kDa subunit of the intact ( $H^+$ )-ATPase recognizes the 100-kDa subunit of  $V_0$ . Tryptic cleavage of the  $V_0$  complex gives the same pattern of fragments for the 100- and 38-kDa subunits as in the intact complex, but with an increase in sensitivity, suggesting greater exposure of these subunits in free  $V_0$ . Proton conduction was measured in reconstituted vesicles containing the  $V_0$  domain and in native vesicles stripped of  $V_1$ . No DCCD-inhibitable proton conduction was observed in either preparation, suggesting that unlike the corresponding  $F_0$  domain of  $F_1F_0$ , the free  $V_0$  domain is not an open proton channel.

The vacuolar ( $H^+$ )-ATPases<sup>1</sup> are responsible for acidification of intracellular compartments in eukaryotic cells, a function that is crucial for a variety of cellular processes (1-3). Vacuolar ( $H^+$ )-ATPases have been isolated from a number of sources, including clathrin-coated vesicles (4), chromaffin granules (5, 6), kidney microsome (7), and the vacuoles of *Neurospora* (8), plants (9, 10), and yeast (11, 12).

In addition to sharing many structural and functional prop-

erties (1), the vacuolar ( $H^+$ )-ATPases also closely resemble the  $F_1F_0$  class of ( $H^+$ )-ATPases (13-16). This is true in terms of both the overall structure (17-19) and in the sequence homology observed between certain subunits (20-26). Thus the A and B subunits of the V-ATPases and the  $\alpha$  and  $\beta$  subunits of  $F_1$  are all derived from a common ancestral nucleotide binding protein (20-25), whereas the c subunit of the V-ATPases appears to have arisen by a gene duplication and fusion of the gene encoding the corresponding c subunit of  $F_0$  (26).

Like the F-type ATPases, the V-ATPases are composed of a peripheral set of polypeptides (termed  $V_1$ ) and an integral set of polypeptides (termed  $V_0$ ) (19). We have demonstrated previously that these two domains could be dissociated and reassembled into a functional ( $H^+$ )-ATPase (27). Because of the similarity between the V- and F-type ATPases, it was of interest to determine whether, as with the  $F_0$  domain, the  $V_0$  domain remained assembled as a discrete macromolecular complex in detergent. We also wished to compare the structural properties of the  $V_0$  subunits in the free  $V_0$  domain with those observed in the intact  $V_1V_0$  complex. Finally, by analogy with  $F_0$ , we have investigated the ability of the  $V_0$  domain to act as a passive DCCD-inhibitable proton channel.

### EXPERIMENTAL PROCEDURES

**Materials**—Calf brains were obtained fresh from a local slaughterhouse.  $C_{12}E_8$ , cholesterol, cholic acid, potassium iodide, DCCD, and ATP (grade II) were purchased from Sigma. Phosphatidylcholine and phosphatidylserine were obtained as chloroform solutions from Avanti Polar Lipids, Inc. and stored at  $-20^\circ C$ . Acridine orange was purchased from Eastman Kodak and 9-amino-6-chloro-2-methoxyacridine (ACMA) was purchased from Molecular Probes. p-Nitro blue tetrazolium chloride, 5-bromo-4-chloro-3-indolyl phosphate (toluidine salt), and affinity-purified goat anti-mouse IgG conjugated to alkaline phosphatase were obtained from Bio-Rad.

**Preparation of Stripped Vesicles**—Clathrin-coated vesicles were prepared from calf brain as described previously (28). Vesicles were stripped of their clathrin coat by dilution (40-fold) into 5 mM Tris (pH 8.5), 150 mM sucrose, and 0.5 mM EDTA followed by incubation for 1 h at  $23^\circ C$  and sedimentation for 1 h at  $100,000 \times g$ . Stripped vesicles displayed a 10-fold higher specific activity for the ( $H^+$ )-ATPase relative to intact coated vesicles.

**Glycerol Density Gradient Separation of  $V_1V_0$  and  $V_0$  Complexes**—Glycerol density gradient sedimentation was carried out by a modification of the procedure described previously (4). Stripped vesicles (1.0 mg of protein/ml) were solubilized with 1.0%  $C_{12}E_8$  containing 0.4 mg of phosphatidylcholine/ml and 0.2 mg of phosphatidylserine/ml in solubilization buffer (50 mM NaCl, 30 mM KCl, 20 mM HEPES (pH 7.0), 0.2 mM EGTA, 10% glycerol, 2 mM 2-mercaptoethanol) for 5 min at  $23^\circ C$  followed by 15 min at  $4^\circ C$ . The insoluble material was removed by sedimentation at  $150,000 \times g$  for 1 h in a Beckman SW 50.1 rotor, and 0.5 ml of the solubilized mixture was applied to an 11-ml 12-25% linear glycerol gradient prepared in solubilization buffer containing 0.02%  $C_{12}E_8$ , 8  $\mu$ g of phosphatidylcholine/ml and spun for 16 h at 38,000 rpm in a Beckman SW-41 rotor. The resultant gradients were fractionated from the bottom using a peristaltic pump to give 19-20 fractions of 0.55-0.60 ml/fraction. The intact  $V_1V_0$  complex, which has a molecular weight 700,000-750,000 (17), typically peaks in fractions 4-6, whereas the dissociated  $V_0$  domain, containing

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<sup>1</sup> The abbreviations used are: ( $H^+$ )-ATPase, proton-translocating adenosine triphosphatase;  $C_{12}E_8$ , polyoxyethylene-9-lauryl ether; ACMA, 9-amino-6-chloro-2-methoxyacridine; DCCD, N,N'-dicyclohexylcarbodiimide; HEPES, 4-(2-hydroxyethyl)-1-piperazineethanesulfonic acid; EGTA, [ethylenbis(oxyethylene)nitri]tetraacetic acid; SDS, sodium dodecyl sulfate; PAGE, polyacrylamide gel electrophoresis; TLCK, 1-chloro-3-tosylamido-7-amino-2-heptanone; CCCP, carbonyl cyanide p-chlorophenylhydrazone.

the 100-, 38-, 19-, and 17-kDa subunits, typically peaks in fractions 10–12. Comparison with the sedimentation behavior of proteins of known molecular weight indicates the free V<sub>0</sub> complex has a molecular weight of approximately 250,000 (data not shown).

**Dissociation of the (H<sup>+</sup>)<sup>+</sup>-ATPase V<sub>0</sub> Domain.** Dissociation of the peripheral V<sub>1</sub> domain was carried out essentially as described previously (27). Stripped vesicles (1.0 mg of protein/ml) were treated with 0.40 M KI and 5.0 mM ATP in buffer containing 20 mM HEPES (pH 7.0), 0.2 mM EGTA, and 2 mM 2-mercaptoethanol for 1 h at 4 °C and then sedimented for 1 h at 150,000 × g in a Beckman SW-50.1 rotor. The KI/ATP stripped membranes were then solubilized with C<sub>12</sub>E<sub>8</sub> and the solubilized protein separated by glycerol density gradient sedimentation as described above.

**<sup>14</sup>C/DCDD Labeling of the 17-kDa c Subunit of the V<sub>0</sub> Domain.** [<sup>14</sup>C]DCDD labeling of the 17-kDa c subunit of the V<sub>0</sub> domain was carried out as described previously for labeling of the c subunit of the intact V<sub>0</sub> complex (29). To 500 µl of the peak V<sub>0</sub> containing fraction from the glycerol density gradient (6.0 µg of protein) was added 50 µl [<sup>14</sup>C]DCDD (specific activity 85 mCi/mmol), and the reaction was allowed to proceed for 30 min at 25 °C. The reaction was then stopped by precipitation of the protein using 6% trichloroacetic acid. Incubation for 30 min at 4 °C, sedimentation for 5 min at 10,000 × g, solubilization of the precipitated protein using Laemmli sample buffer and separation of the solubilized polypeptides on a 13.5% acrylamide gel as described below. Following electrophoresis, the gel was washed for 15 min in 10% acetic acid, 10% isopropyl alcohol, impregnated with ENHANCE (Du Pont-New England Nuclear), dried under vacuum, and exposed to Kodak XAR-5 film for 7 days at -70 °C using an intensifier screen.

**Chloroform-Methanol Extraction of the 17-kDa c Subunit of V<sub>0</sub>.** Chloroform-methanol extraction was carried out essentially as described previously (29). 400 µl of the V<sub>0</sub> containing fraction (4.8 µg of protein) was placed in a 15-ml conical glass centrifuge tube to which was added 5 volumes of chloroform:methanol (2:1, v/v). The sample was vortexed vigorously and incubated on ice, with occasional vortexing, for 1 h. The sample was then spun for 5 min at 5,000 × g in a table top centrifuge, the upper aqueous phase and the interface (containing most of the denatured protein) was carefully removed, and the lower organic phase was transferred to a separate tube and dried under nitrogen. The extracted protein was then solubilized using 200 µl of Laemmli sample buffer and 30 or 60 µl were run on a 12.5% acrylamide gel as described below.

**Western Blot Analysis.** The presence of a 100-kDa polypeptide in the V<sub>0</sub> domain capable of reacting with a monoclonal antibody specific for the 100-kDa subunit of the intact V<sub>0</sub> complex was demonstrated by Western blot analysis as follows. Membranes from which the clathrin had been stripped (1 mg of protein/ml) were solubilized with C<sub>12</sub>E<sub>8</sub> and the solubilized proteins separated by glycerol density gradient sedimentation as described above. 60-µl aliquots of each fraction were solubilized with Laemmli sample buffer and applied to a 12% acrylamide gel. After electrophoresis, the proteins were transferred electrophoretically to nitrocellulose by blotting at 100 mA for 16 h at 4 °C using a Bio-Rad Trans Blot cell and a transfer buffer containing 25 mM Tris, 192 mM glycine (pH 8.3), 20% methanol.

After transfer, the blot was washed twice in TBS (20 mM Tris (pH 7.5), 0.5 M NaCl) and then incubated for 30 min in TBS containing 1.5% gelatin. After blocking, the blot was washed twice in TTBS (TBS containing 0.05% Tween 20) followed by incubation for 2 h in TTBS containing 0.05% gelatin and a 1:50 dilution of the monoclonal antibody 3A-1B. The blot was then washed three times in TTBS and incubated for 1 h in TTBS containing 0.5% gelatin and a 1:100 dilution of a goat anti-mouse IgG conjugated to alkaline phosphatase (Bio-Rad). After incubation with the secondary antibody, the blot was washed once in TTBS and twice in TBS and then developed by incubation for 20 min in 0.1 M sodium carbonate (pH 9.8), 1 mM MgCl<sub>2</sub> containing 0.3% p-nitro blue tetrazolium phosphate (toluidine salt) and 0.015% 5-bromo-4-chloro-3-indolyl phosphate. The blot was then washed with water and air-dried.

**Proteolysis of the V<sub>0</sub> Domain.** The gradient fractions containing either the intact V<sub>0</sub> complex (1.8 µg of protein) or the V<sub>0</sub> domain (1.2 µg of protein) were treated with 0–1.0 µg of trypsin for 4 h at 25 °C. The proteolysis was then stopped by addition of 5 mM TLCK followed by SDS-PAGE on a 12% acrylamide gel and silver staining as described below.

**Reconstitution of the V<sub>0</sub> Domain into Phospholipid Vesicles.** The procedure used in reconstitution of the V<sub>0</sub> domain is based on the protocol employed to reconstitute the intact V<sub>0</sub> complex (4). The glycerol density gradient fractions containing the peak of the

polypeptides (typically fractions 10–12) from either native membranes or membranes treated with KI/ATP were concentrated 2-fold using a Centricon 10 microconcentrator. To 1.0 ml of the concentrated V<sub>0</sub> was added 0.2 ml of 5% cholate, 4 mg of phosphatidylcholine/ml, and 2 mg of phosphatidylserine/ml in solubilization buffer followed by 0.34 ml 10% cholate, 4 mg of cholesterol/ml and 7 mg of phosphatidylcholine/ml in 150 mM NaCl, 2 mM 2-mercaptoethanol. The mixture was incubated for 5 min at 23 °C and then 10 min at 4 °C followed by dialysis for 2 days against five changes of 200 volumes of solubilization buffer using Spectrapor-2 dialysis tubing with a M<sub>w</sub> cutoff of 12,000–14,000. As previously described, reconstitution of the intact V<sub>0</sub> complex under these conditions gave rise to reconstituted vesicles capable of ATP-dependent proton uptake as assayed by uptake of acridine orange (4).

**Measurement of Passive Proton Flux in Reconstituted Vesicles Containing the V<sub>0</sub> Domain or Native Membranes from Which the V<sub>1</sub> Domain Had Been Dissociated.** The V<sub>0</sub> domain (12 µg of protein) was reconstituted into phospholipid vesicles as described above except the dialysis buffer contained 150 mM KCl, 20 mM HEPES (pH 7.0), 0.2 mM EGTA, 2 mM 2-mercaptoethanol, 10% glycerol. The vesicles were then diluted 1:20 into 150 mM NaCl, 20 mM HEPES (pH 7.0), 0.2 mM EGTA, 2 mM 2-mercaptoethanol, 10% glycerol, 0.5 mg of bovine serum albumin/ml, and 2 µM ACMA. To initiate proton flux, a membrane potential was generated by addition of 20 µM valinomycin. The resultant proton uptake was monitored by fluorescence quenching of ACMA using excitation and emission wavelengths of 410 and 490 nm, respectively. As a negative control, reconstituted vesicles lacking protein were prepared and assayed in an identical manner. As a positive control, each vesicle preparation was tested for its ability to generate a membrane potential driven proton flux following addition of 1.0 µM of the proton ionophore CCCP.

Stripped vesicles (1.5 mg of protein/ml) that had been treated with KI and ATP as described above were loaded with potassium by permeabilization with 0.7% cholate, 0.4 µg of phosphatidylcholine/ml, 0.2 µg of phosphatidylserine/ml followed by dialysis against four changes of 200 volumes of 100 mM K<sub>2</sub>SO<sub>4</sub>, 20 mM HEPES (pH 7.0), 0.2 mM EGTA, 10% glycerol, 2 mM 2-mercaptoethanol overnight. Potassium sulfate rather than potassium chloride was employed in experiments with native vesicles to avoid dissipation of the K<sup>+</sup>/valinomycin-induced membrane potential by the chloride channel which is present in these vesicles (30, 31). Proton flux was then measured by ACMA quenching in response to a potassium/valinomycin-induced membrane potential as described above. As a negative control, a second batch of vesicles was prepared in an identical fashion except that they were treated with 50 µM DCCD for 1 h at 4 °C prior to measurement of proton flux. Membrane potential driven proton flux on addition of CCCP was also tested as described above.

**Gel Electrophoresis.** SDS-polyacrylamide gel electrophoresis was carried out using 12, 12.5, or 13.5% acrylamide gels by the method of Laemmli (32). Following electrophoresis, gels were fixed for at least 2 h in 30% methanol, 7.5% acetic acid prior to silver staining by the method of Oakley et al. (33).

## RESULTS

Fig. 1A shows the protein pattern obtained after solubilization of coated vesicle membrane proteins with C<sub>12</sub>E<sub>8</sub>, separation on 12–25% glycerol density gradients, and SDS-PAGE. As can be seen, the V<sub>0</sub> subunits of molecular masses 100, 38, 19, and 17 kDa migrate at two distinct positions on the density gradients. The heavier complex, which sediments with a molecular weight of 700,000–750,000 (17), corresponds to the intact V<sub>0</sub> complex and thus has the complete complement of nine subunits. The lighter complex (fractions 9–11), which by comparison with the V<sub>1</sub>V<sub>0</sub> complex and other marker proteins, has a molecular weight of approximately 250,000, contains the V<sub>0</sub> subunits but not the V<sub>1</sub> subunits. There are also present a variety of contaminating proteins which do not peak with the V<sub>0</sub> subunits. We have demonstrated previously that the V<sub>0</sub> subunits are present in the V<sub>1</sub>V<sub>0</sub> complex with a stoichiometry of (100,000), (38,000), (19,000), and (17,000), (17). As can be seen by comparing the relative staining intensities of the V<sub>0</sub> subunits in the two complexes, this same stoichiometry appears to apply to the free V<sub>0</sub> domain. If the vesicles are first treated with KI and ATP (Fig. 1B), the V<sub>0</sub>

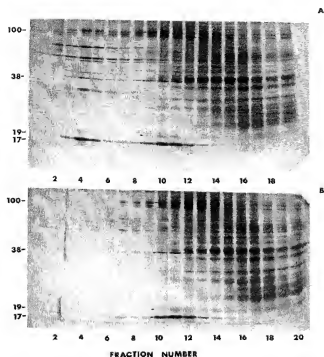


FIG. 1. Glycerol density gradient separation of  $C_{12}E_8$  solubilized  $V_1V_0$  and  $V_0$  complexes. *A*, stripped vesicles (1.0 mg of protein/ml) were solubilized with  $C_{12}E_8$  and the solubilized proteins separated by sedimentation on a 12–25% glycerol density gradient as described under "Experimental Procedures." 60  $\mu$ l of each fraction was applied to a 12% acrylamide gel, and SDS-PAGE was carried out by the method of Laemmli (32). The bottom of the gradient corresponds to fraction 1, and the molecular masses of the  $V_0$  subunits (in kDa) are indicated to the left. The  $V_0$  subunits peak in fraction 4, corresponding to the intact  $V_1V_0$  complex, and fraction 10, corresponding to the free  $V_0$  complex. *B*, stripped vesicles (1.0 mg of protein/ml) were treated with KI and ATP as described under "Experimental Procedures" and then solubilized with  $C_{12}E_8$  and separated by glycerol density gradient sedimentation as described in *A*. The  $V_0$  subunits appear only in the lighter complex which, on this gradient, peaks in fraction 11.

subunits migrate entirely in the lighter complex. The slight shift in position of the  $V_0$  complex in Fig. 1*B* relative to Fig. 1*A* corresponds to small variations between individual glycerol density gradient runs. These results suggest that the lighter complex corresponds to the free  $V_0$  domain which remains assembled after either detergent solubilization or KI/ATP treatment and that there is an excess of  $V_0$  domains in the native vesicle over that required to form functional  $V_1V_0$  complexes.

To test whether the 100-, 38-, 19-, and 17-kDa polypeptides migrating as a complex of 250,000 correspond to the authentic  $V_0$  subunits, the following tests were performed. First, the ability of [ $^{14}C$ ]DCCD to label the 17-kDa (c) subunit was tested. As can be seen in Fig. 2*A*, the c subunit of  $V_0$ , like that in the intact  $V_1V_0$  complex (29), was labeled by [ $^{14}C$ ]DCCD. In addition to labeling of the 17-kDa c subunit, a small amount of label was also observed at approximately 100 kDa. This may correspond to some labeling of the 100-kDa subunit, labeling of a different 100-kDa polypeptide, or to partial aggregation of the 17-kDa subunit, which is present in a stoichiometry of six copies per complex (17). In addition to labeling by [ $^{14}C$ ]DCCD, the 17-kDa polypeptide present in the  $V_0$  containing fraction was extracted by chloroform:methanol (Fig. 2*B*), as demonstrated previously for the authentic c subunit (29). Thus in both its reactivity toward

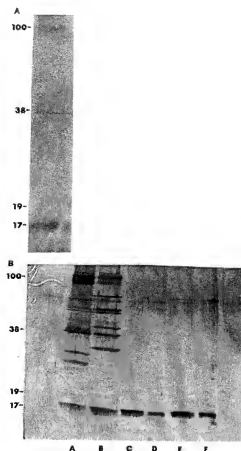


FIG. 2. [ $^{14}C$ ]DCCD labeling and chloroform:methanol extraction of the 17-kDa c subunit of the  $V_0$  complex. *A*, 500  $\mu$ l of the peak  $V_0$  fraction (6.0  $\mu$ g of protein) was reacted with 50  $\mu$ M [ $^{14}C$ ]DCCD for 30 min at 23  $^{\circ}C$  followed by precipitation with trichloroacetic acid, separation on a 13.5% acrylamide gel, and autoradiography as described under "Experimental Procedures." *B*, 400  $\mu$ l of the peak  $V_0$  fraction (4.8  $\mu$ g of protein) or the peak  $V_1V_0$  fraction (7.2  $\mu$ g of protein) were extracted with 5 volumes of chloroform:methanol (2:1, v/v) and the proteins extracted into the organic phase solubilized in 200  $\mu$ l of Laemmli sample buffer as described under "Experimental Procedures." *Lanes C and D*, 60 and 30  $\mu$ l of the protein extracted from the  $V_0$  fraction, respectively; *lanes E and F*, 60 and 30  $\mu$ l of the protein extracted from the  $V_1V_0$  fraction, respectively. *Lane A*, an aliquot of the unextracted  $V_0$  fraction equivalent to that employed in *lane D*. *Lane B*, an aliquot of the unextracted  $V_1V_0$  fraction equivalent to that employed in *lane F*. The molecular masses of the  $V_0$  subunits (in kDa) are shown to the left.

DCCD and its hydrophobicity, the c subunit of the  $V_0$  complex was indistinguishable from the c subunit of  $V_1V_0$ .

As a further test of the relationship between these two complexes, Western blot analysis was performed using a monoclonal antibody specific for the 100-kDa subunit of the coated vesicle ( $H^+$ )-ATPase. Fig. 3 shows that this monoclonal antibody recognized the 100-kDa subunit in both the intact  $V_1V_0$  complex and in isolated  $V_0$ . Silver staining of a parallel SDS-PAGE gel run on the same gradient fractions indicated that, for this glycerol density gradient, the 38-, 19-, and 17-kDa polypeptides, like the 100-kDa immunoreactive band, peaked in fractions 6 and 12 (data not shown). This data provide strong evidence for the identity of the 100-kDa polypeptide in these two complexes.

To further characterize the  $V_0$  domain, proteolysis was carried out on both the  $V_1V_0$  and  $V_0$  complexes in the detergent solubilized state. We have demonstrated previously that

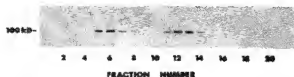


FIG. 3. Western blot analysis of glycerol density gradient fractions of  $C_{12}E_9$ -solubilized stripped vesicle membrane proteins using the 100-kDa-reactive monoclonal antibody 3A-6D. Stripped vesicles (1.0 mg of protein/ml) were solubilized with  $C_{12}E_9$  and the solubilized proteins separated by glycerol density gradient sedimentation as described in Fig. 1A. 60  $\mu$ l of each fraction was applied to a 12% acrylamide gel and SDS-PAGE, and electrophoretic transfer to nitrocellulose and Western blotting using the monoclonal antibody 3A-6D and goat anti-mouse IgG conjugated to alkaline phosphatase were carried out as described under "Experimental Procedures." Silver staining of a second polyacrylamide gel run on the same gradient fractions indicated that the 38-, 19-, and 17-kDa polypeptides, like the 100-kDa immunoreactive band, peaked in fractions 6 and 12.

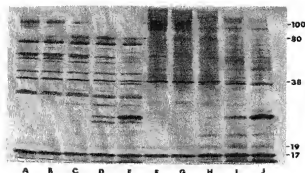


FIG. 4. Trypsin digestion of detergent-solubilized  $V_0$  and  $V_0$  complexes. Peak gradient fractions containing either intact  $V_0$  or  $V_0$  complex (lanes A-E) (1.8  $\mu$ g of protein) or the free  $V_0$  domain (lanes F-J) (1.2  $\mu$ g of protein) were treated with 0 (lanes A and F), 0.001 (lanes B and G), 0.01 (lanes C and H), 0.10 (lanes D and I), or 1.0 (lanes E and J)  $\mu$ g trypsin for 4 h at 23  $^{\circ}$ C. Proteolysis was stopped by addition of 5 mM TLCK, and the samples were run on a 12% acrylamide gel followed by silver staining as described under "Experimental Procedures." The positions of the  $V_0$  subunits and the 80-kDa fragment of the 100-kDa subunit are indicated at the right of the figure.

trypsin treatment of the intact ( $H^+$ )-ATPase generates an 80-kDa fragment of the 100-kDa subunit and cleaves the 38-kDa polypeptide approximately 1–2 kDa from the amino terminus (18). Moreover, both of these cleavage sites were shown to be present on the cytoplasmic side of the membrane (18). As can be seen in Fig. 4, the same proteolytic cleavage pattern is obtained for the 100- and 38-kDa polypeptides in the free  $V_0$  domain. The fact that these cuts happen at somewhat lower trypsin concentrations for  $V_0$  than for  $V_0$  suggests that there is greater accessibility of the protease to these polypeptides in the free  $V_0$  complex. That the same pattern is observed for both detergent-solubilized and reconstituted  $V_0$  (data not shown) indicates that, like the intact  $V_0$  complex, the free  $V_0$  domain reconstitutes primarily with the cytoplasmic face exposed.

To test whether the  $V_0$  domain could function as a passive proton channel, the following protocol was employed. The detergent-solubilized  $V_0$  domain from either untreated vesicles or vesicles which had been treated with KI and ATP was isolated by density gradient sedimentation as shown in Fig. 1 and then reconstituted into phospholipid vesicles by cholate dialysis as described previously (4). The vesicles were reconstituted in the presence of 150 mM KCl and then diluted into

a potassium free buffer in order to establish a large potassium gradient across the membrane. The vesicles were incubated in the presence of the fluorescence dye ACMA, and the assay was initiated by addition of valinomycin. Because of the substantial potassium gradient present across the vesicle membrane, addition of valinomycin generated a negative interior membrane potential which acted as a driving force for proton uptake, which was monitored by fluorescence quenching of ACMA. Vesicles lacking protein acted as the negative control, whereas addition of the proton ionophore CCCP acted as the positive control. As can be seen in Fig. 5A, no greater passive proton transport was observed in vesicles containing  $V_0$  than was observed in vesicles lacking protein, despite the substantial fluorescence quenching observed on addition of CCCP. Moreover, treatment of reconstituted  $V_0$  with DCCD had no effect on this low background level of proton leakage (data not shown).

Because it is possible that the  $V_0$  domain may have become inactivated during the course of isolation and reconstitution, we also tested to see whether the  $V_0$  domain remaining in the native membrane after dissociation of  $V_1$  with KI and ATP could conduct protons. Native vesicles were loaded with potassium by permeabilization with cholate plus phospholipid followed by removal of the detergent by dialysis. We have observed that cholate is ineffective at solubilization of either the  $V_0$  domain or the intact  $V_0$  under these conditions (data not shown). As shown in Fig. 5B, the  $V_0$  domain in the native membrane is also incapable of DCCD-inhibitable proton translocation, despite the fact that, as we have demonstrated previously (27), this  $V_0$  is competent to reassemble with the  $V_1$  domain to give an active ( $H^+$ )-ATPase complex.

## DISCUSSION

The  $V_0$  domain of the coated vesicle ( $H^+$ )-ATPase is composed of four subunits of molecular weight 100,000, 38,000, 19,000, and 17,000 (19). They are operationally defined as integral subunits by the observation that they remain attached to the membrane after dissociation of the peripheral  $V_1$  subunits by chaotropic agents such as KI and  $KNO_3$  (19). In the present manuscript we provide the first demonstration that these integral subunits remain assembled as a complex following detergent solubilization. This complex has an approximate molecular weight of 250,000 and, by comparison with the intact  $V_0$  complex (17), has a subunit stoichiometry of one copy each of the 100-, 38-, and 19-kDa subunits and six copies of the 17-kDa subunit. The ability of the  $V_0$  subunits to remain assembled as a complex in detergent solution has also recently been reported for the vacuolar ( $H^+$ )-ATPase from *Neurospora* (34).

As can be seen from Fig. 1, coated vesicles appear to contain an excess of  $V_0$  domains over what is required to form functional  $V_1V_0$  complexes. It was therefore important to compare the properties of the polypeptides present in these "excess"  $V_0$  domains with the "authentic"  $V_0$  subunits to determine whether they were the same. According to the following criteria, the  $V_0$  polypeptides present in these two populations of  $V_0$  are identical: 1) [ $^{14}C$ ]DCCD labeling and chloroform:methanol extraction of the 17-kDa a subunit; 2) reaction of the 100-kDa polypeptide with a specific monoclonal antibody by Western blot; 3) tryptic cleavage pattern of both the 100- and 38-kDa subunits. With respect to proteolysis, it is interesting to note that although the same tryptic fragments of the 100- and 38-kDa subunits are generated, proteolysis appears to occur at lower trypsin concentrations for the free  $V_0$  domain relative to the intact  $V_1V_0$  complex, suggesting that removal of the  $V_1$  domain has increased the accessibility

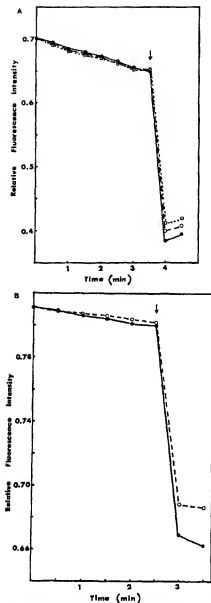


FIG. 5. Measurement of passive proton flux in reconstituted vesicles or native membranes containing  $V_0$ . A, peak gradient fractions containing  $V_0$  (12  $\mu$ g of protein) were obtained following detergent-solubilization of either native stripped vesicles (□) or membranes treated with KI and ATP (○) as described in Fig. 1. Reconstitution was then carried out either in the presence (□) or absence (○) of protein as described under "Experimental Procedures." Reconstituted vesicles (25  $\mu$ l containing 0.6  $\mu$ g of protein) which had been prepared in buffer containing 150 mM KCl were then diluted 1:20 into buffer containing NaCl in place of KCl plus 2  $\mu$ M ACMA. At  $t = 0$ , membrane potential driven proton flux was initiated by addition of 20 nM valinomycin and proton uptake was monitored by fluorescence quenching of ACMA ( $\lambda_{ex} = 410$  nm,  $\lambda_{em} = 490$  nm). At the arrow, the vesicles were made permeable to protons by the addition of 1.0  $\mu$ M CCCP. B, stripped vesicles (1.5 mg of protein/ml) that had been treated with KI and ATP as described in Fig. 1 were loaded with 100 mM  $K_2SO_4$  as described under "Experimental Procedures" and then treated for 1 h at 4 °C either in the absence (○) or presence (□) of 50  $\mu$ M DCCD. Vesicles (25  $\mu$ l containing 38  $\mu$ g of protein) were then diluted 1:20 into buffer containing  $Na_2SO_4$  in place of  $K_2SO_4$ , and at  $t = 0$ , potential driven proton uptake was initiated by addition of 20 nM valinomycin and monitored by fluorescence quenching of ACMA as described above. At the arrow, the vesicles were permeabilized to protons by addition of 1.0  $\mu$ M CCCP.

of the 100- and 38-kDa subunits to proteolytic cleavage.

Why there is an excess of  $V_0$  domains in coated vesicles remains uncertain. It does not seem to be due to loss of the corresponding  $V_1$  domains during dissociation of the elastrin coat or detergent solubilization and density gradient sedimentation of the  $(H^+)$ -ATPase, since Western blot analysis of fractions obtained throughout this procedure using the monoclonal antibody 3.2-F1 (specific for the peripheral A subunit (30)) does not indicate any significant loss of  $V_1$  during these steps (data not shown). It is possible that some loss of  $V_1$  domains occurs during isolation of the elastrin-coated vesicles from bovine brain. Alternatively, there may exist a pool of unassembled  $V_0$  domains in the cell. Consistent with this idea is the observation that in MDBK cells we are able to detect a pool of unassembled  $V_1$  domains.<sup>2</sup> The possible implications of these findings for regulation of vacuolar acidification are discussed below.

It has been demonstrated by a number of laboratories (35–37) that the F<sub>0</sub> domain of the F<sub>1</sub>F<sub>0</sub>  $(H^+)$ -ATPases can act as a passive DCCD-inhibitable proton channel. Because of the similarity between the vacuolar and F<sub>1</sub>F<sub>0</sub> classes of  $(H^+)$ -ATPase, both in overall structure (17–19) and in sequence homology (20–26), it was of interest to determine whether the  $V_0$  domain, like F<sub>0</sub>, could conduct protons. We investigated this question using both the isolated, reconstituted  $V_0$  domain and native membrane vesicles from which the  $V_1$  domains had been removed by treatment with KI and ATP (19). Proton movement was driven using a K<sup>+</sup>/valinomycin-induced membrane potential and measured using uptake of the fluorescence dye ACMA. As can be seen in Fig. 5, in neither case did the  $V_0$  domain exhibit DCCD-inhibitable proton translocation. We have shown previously that following dissociation of the peripheral subunits with KI and ATP, the  $V_0$  domain remaining in the membrane is competent to assemble with  $V_1$  to form a functional  $(H^+)$ -ATPase (27). Thus treatment with KI and ATP has not rendered the  $V_0$  domain nonfunctional. These results suggest that, unlike F<sub>0</sub>, the free  $V_0$  domain is not an open proton channel.

This absence of proton conduction by  $V_0$  is interesting in a number of respects. First, it has been reported previously that the 17-kDa c subunit of the coated vesicle  $(H^+)$ -ATPase, when extracted with toluene and reconstituted into phospholipid vesicles, was itself competent to form a DCCD-inhibitable proton channel (38). Although surprising in light of the lack of channel activity of the isolated homologous c subunit of F<sub>0</sub> (37), if correct this result would suggest that one or more of the remaining  $V_0$  subunits is suppressing the channel activity of the c subunit. A second question concerns why if the fully assembled F<sub>0</sub> domain conducts protons, the corresponding  $V_0$  domain does not. One possible answer is that the cell employs assembly of  $V_1V_0$  as a mechanism of controlling vacuolar acidification. According to this model, acidification would be activated in a particular compartment by attachment of  $V_1$  to free  $V_0$  domains preexisting in the corresponding membrane. It would be important under these circumstances that free  $V_0$  not conduct protons since otherwise, in any membrane containing multiple  $V_0$  domains, it would be impossible to establish any significant pH gradient until all of the available  $V_0$  sites had been occupied. Whether free  $V_0$  domains exist in the cell and what factors might control assembly of  $V_1$  and  $V_0$  *in vivo* remain important but unanswered questions.

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<sup>2</sup> M. Myers and M. Forgac, manuscript in preparation.

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